Evaluation of Closed-Loop Site-Specific Irrigation with Wireless Sensor Network

Y. Kim[1]; R. G. Evans[2]; and W. M. Iversen[3]

Abstract: Automated site-specific sprinkler irrigation system can save water and maximize productivity, but implementing automated irrigation is challenging in system integration and decision making. A controllable irrigation system was integrated into a closed-loop control with a distributed wireless in-field sensor network for automated variable-rate irrigation. An experimental field was configured into five soil zones based on soil electrical conductivity. In-field soil water sensors were installed on each zone of the distributed wireless sensor network and remotely monitored by a base station for decision making. The soil water sensors were calibrated with a neutron probe and individually identified for their response ranges at each zone. Irrigation decisions were site-specifically made based on feedback of soil water conditions from distributed in-field sensor stations. Variable-rate water application was remotely controlled by the base station to actuate solenoids to regulate the amount of time an individual group of sprinkler nozzles was irrigating in a 60-s time period. The performance of the system was evaluated with the measurement of water usage and soil water status throughout the growing season. Variable water distribution collected in catch cans highly matched to the rate assigned by computer with $r^2=0.96$. User-friendly software provided real-time wireless irrigation control and monitoring during the irrigation operation without interruptions in wireless radio communication.

DOI: 10.1061/(ASCE)0733-9437(2009)135:1(25)

CE Database subject headings: Sprinkler irrigation; Water management; Sensors; Control systems; Automation.

Introduction

Common variations in soil properties and soil water availability over large fields are appropriate for site-specific irrigation management. Development of automated site-specific sprinkler irrigation systems allow producers to maximize irrigation efficiency, simultaneously minimizing negative effects on their productivity. A distributed in-field wireless sensor network (WSN) and a variable-rate irrigation controller offer a potential means to support automated closed-loop irrigation control, but the seamless integration of the WSN and irrigation controller can be challenging.

The spatial variability of soils and other characteristics in agricultural fields has been addressed in the precision agriculture literature (Irmak et al. 2002; Ahmad et al. 1999). However, optimizing configurations for site-specific management in each field remains a difficult task. Apparent soil electrical conductivity (EC) mapping has been widely used as one way to characterize soil variability of agricultural fields (Farahani and Buchleiter 2004; Drummond et al. 2000; Jabro et al. 2006). In-field wireless sensing systems and variable-rate irrigation systems have also been studied by many researchers (Shock et al. 1999; King et al. 2000; Marinda et al. 2003; Wall and King 2004; Perry et al. 2004; Kim et al. 2006a). However, few have fully integrated these systems into closed-loop wireless irrigation control and monitoring systems.

A wireless irrigation control system was developed and evaluated for real-time variable-rate irrigation control and monitoring (Kim et al. 2006a), and a distributed WSN was designed for in-field wireless sensing of soil water conditions (Kim et al. 2007b). The objective of this paper is to evaluate the integration of the irrigation control system with the in-field WSN for automated closed-loop variable-rate sprinkler irrigation. This research is part of a project that was established in early 2004 to develop integrated wireless networks of in-field sensing and irrigation control systems for real-time irrigation decision support by USDA-ARS, Northern Plains Agricultural Research Laboratory near Sidney, Mont.

[1]Research Associate, USDA-ARS, Northern Plains Agricultural Research Laboratory, 1500 N. Central Ave., Sidney, MT 59270. E-mail: james.kim@ars.usda.gov

[2]Research Leader, USDA-ARS, Northern Plains Agricultural Research Laboratory, 1500 N. Central Ave., Sidney, MT 59270. E-mail: robert.evans@ars.usda.gov

[3]Physical Scientist, USDA-ARS, Northern Plains Agricultural Research Laboratory, 1500 N. Central Ave., Sidney, MT 59270. E-mail: bill.iversen@ars.usda.gov

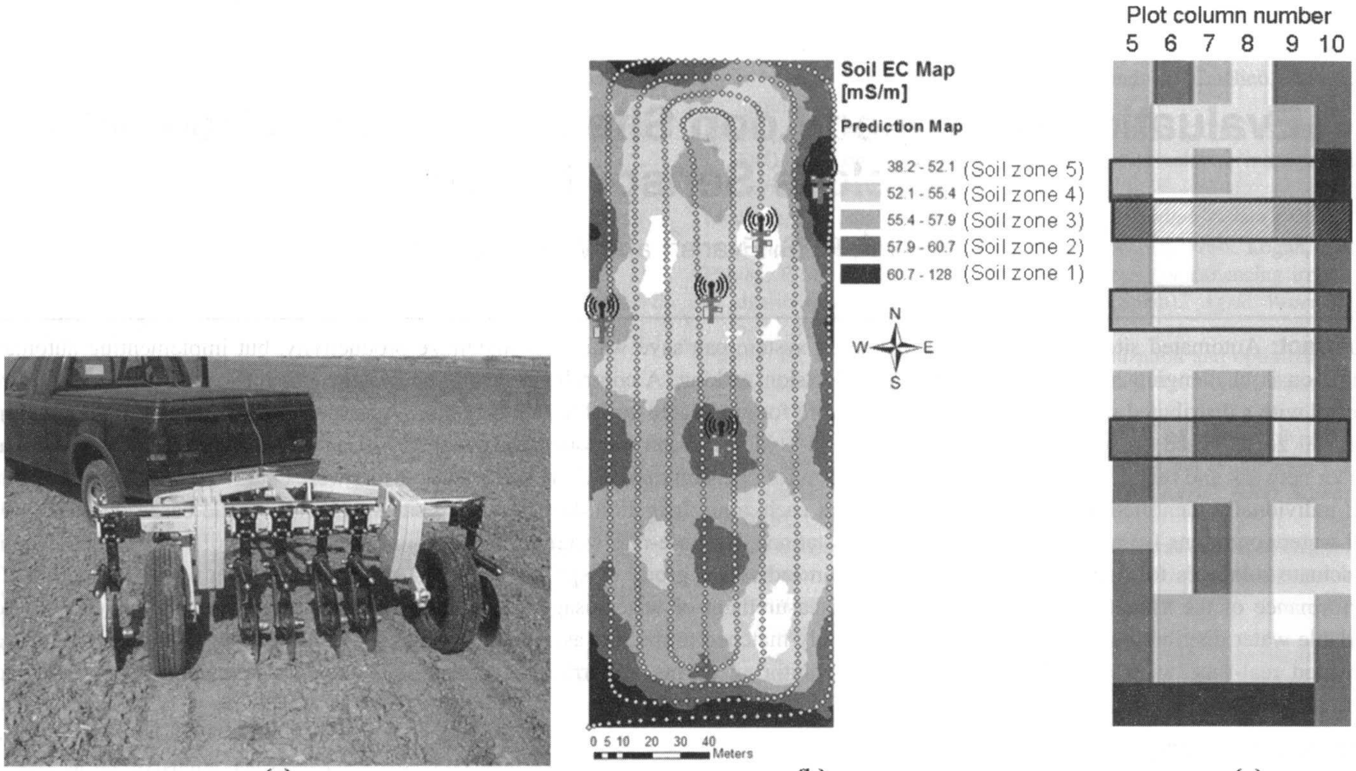
Note. Discussion open until July 1, 2009. Separate discussions must be submitted for individual papers. The manuscript for this paper was submitted for review and possible publication on September 11, 2007; approved on April 21, 2008. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 135, No. 1, February 1, 2009.

Materials and Methods

Site-Specific Field Configuration

Mapping of soil EC was used to provide a measure of the spatial variation of an experimental field so that a minimum number of in-field sensor systems could be placed with maximum impact for characterizing the scope of field information. The soil EC was used primarily as an indicator of water holding capacity as well as soil salinity. The distribution of the in-field sensing stations was determined from analysis of these maps (Kim et al. 2005).

The apparent soil EC was mapped by a soil EC mapping system (3100, Veris Technologies, Salina, Kan.) at approximately



(a) (b) (c)

Fig. 1. Site-specific field configuration: (a) Veris soil electrical conductivity (EC) mapping system; (b) WSN topology of five classified zones based on soil EC map; and (c) mosaic map with 6 columns and 15 rows to match the irrigation sprinkler layout, where four rows were used for variable-rate irrigation and a shaded area at the fourth row was used for a field test using catch cans

2.8 m/s travel speed (a sample per second) using a 2.4-m parallel swathing monitored with geo-referenced points using a differential GPS (Ag132, Trimble, Sunnyvale, Calif. with Omnistar correction) on an experimental field [Fig. 1(a)]. Geostatistical analysis was performed using geographic information system software (ArcGIS ver. 9.1, ESRI, Redlands, Calif.) with a Kriging model to interpolate data and create spatial maps with five classifications by a quantile method. Fig. 1(b) shows a WSN topology based on soil EC variations from 38.2 to 128 mS/m with five different zones. One sensing station was placed in each zone, and the five station numbers were labeled the same way as soil zone numbers in descending order of EC values. The map was converted into a mosaic map [Fig. 1(c)] by switching filled-contour to 6×15 grid using software (ArcGIS ver. 9.1, ESRI, Redlands, Calif.) to match the layout of the irrigation sprinkler banks which had total 15 groups of nozzle banks on five spans spaced 15 m/bank and 3 banks/span. Four plot strips at the third, fourth, sixth, and ninth rows were used for the variable-rate irrigation. The rest of rows were treated as conventional irrigation with 100% water application. The 4th row in shade contained all five different soil zones and was used for a field test using catch cans.

Wireless Sensor Network

A distributed WSN was developed for real-time in-field soil sensing. The network consisted of five sensing stations and a weather station. Each of the sensing stations contained a data logger (CR10, Campbell Scientific Inc., Logan, Utah), two soil water reflectometers (CS616, Campbell Scientific Inc., Logan, Utah), horizontally one at the 30 cm and the other at the 61-cm soil depth, and a soil temperature sensor (107, Campbell Scientific Inc., Logan, Utah) at the 15-cm soil depth. The weather station measured precipitation, air temperature, relative humidity, wind speed, wind direction, and solar radiation. Sensors at the in-field sensing and weather stations were scanned every 10 s, and averaged data were stored and wirelessly transmitted every 15 min via a Bluetooth radio transmitter (SD202, Initium Co., Korea) back to a base computer. All components at each station are self-powered by a 12-V battery recharged by a solar panel (SX5, Solarex, Sacramento, Calif.). The design for power management and wireless communication for the WSN was detailed by Kim et al. (2007b).

Wireless Variable-Rate Irrigation

A self-propelled Valley (Valmont Industries, Inc., Valley, Neb.) linear sprinkler irrigation system was used. Site-specific operation was controlled by a programmable logic controller (PLC) (S7-226, Siemens AG, Germany) located on the cart. The PLC managed the activation of electric over pneumatic solenoids to control 30 banks of 5–10 sprinklers each. Variable-rate applications were implemented by controlling the on/off times for groups of spray nozzles based on information from the site-specific field monitoring obtained by the WSN. As the linear sprinkler system moved across the field, a low-cost WAAS-enabled global positioning system (GPS) receiver (17-HVS, Garmin International Inc., Olathe, Kan.) mounted on the top of the linear cart continuously updated the position of the sprinkler nozzles. The GPS receiver was tied directly to the PLC controller, and a radio signal of the GPS position was continuously transmitted to the computer in a base station over the wireless link. The irrigation application depths were adjusted by pulsing sprinkler heads on and off to achieve a target depth based on a digital map of depths for each nozzle

Table 1. Volumetric Water Content of the Time-Domain Reflectometer (TDR) Sensor at the 30-cm Soil Depth (Factory Calibration) Compared to Those of the Neutron Probe (N-Probe) at the 23-cm Soil Depth at Five Different Locations on the Soil Electrical Conductivity (EC) Map (Station 1 at Highest EC, Station 5 at Lowest EC)

	Station 1		Station 2		Station 3		Station 4		Station 5	
Date	N-probe	TDR	N-probe	TDR	N-probe	TDR	N-probe	TDR	N-probe	TDR
June 1, 2006	33.2	50.3	39.0	64.3	34.1	58.1	34.5	47.6	30.8	51.3
June 7, 2006	30.5	39.3	35.6	56.1	30.3	48.8	31.1	39.2	28.6	43.4
June 19, 2006	33.4	44.3	37.7	61.0	34.5	52.4	33.9	43.0	33.1	47.1
June 30, 2006	29.4	38.0	32.2	54.8	32.5	46.4	30.7	40.6	33.6	39.6
July 5, 2006	27.6	33.0	29.9	51.2	30.9	44.9	29.9	35.8	31.1	33.9
July 13, 2006	25.4	31.1	25.0	48.1	29.0	44.2	28.8	33.3	28.5	28.8
July 18, 2006	24.1	30.3	23.7	47.0	28.3	43.7	29.0	32.6	28.0	27.5
Average	29.1	38.0	31.9	54.6	31.4	48.4	31.1	38.9	30.5	38.8
STDev	3.6	7.4	6.0	6.4	2.4	5.3	2.3	5.4	2.3	9.1
Correlation	0.95		0.97		0.81		0.96		0.53	

Note: Correlation coefficients (r) averaged 0.84.

location as the machine moved down the field. Signal interface and software design for the PLC were detailed by Kim et al. (2006b).

Two types of sprinkler heads were used: midelevation spray application (MESA) and low energy precision application (LEPA) (Evans and Iversen 2005). MESA sprinkler heads were a spinning sprinkler (S3000, Nelson Irrigation Corp., Walla Walla, Wash.) with 103 kPa (15 psi) regulators and wetted diameters ranging from 6 to 10 m and spaced every 32 m at about 1 m above the ground, where as LEPA heads were a bubble spray (Quad-Spray, Senninger Irrigation Corp., Clermont, Fla.) with 69 kPa (10 psi) regulators and spaced every 1.2 m along submanifolds suspended from the truss rods at about 15 cm above the furrow surface. Nominal operating pressure of the pump was about 248 kPa (36 psi). When LEPA sprinklers are turned off, the LEPA heads are pulled up by a pneumatic cylinder that is activated by the solenoid.

Closed-Loop Irrigation Control

A closed-loop irrigation control system was developed by integrating in-field sensor stations with the irrigation control station through a base computer station. Prior to inclusion in the closed-loop irrigation control system, each system component was independently tested and validated over the entire 2006 growing season.

The base station wirelessly communicated with both the in-field sensing stations and the irrigation control station in real-time mode. It continuously received in-field sensory data to monitor soil water conditions. A decision support aid was developed on the base computer that determined when to irrigate and how much to apply to each of five classified zones. The base station was located about 700 m away from the field. A patch radio antenna was mounted on the east side of the rooftop and connected to a Bluetooth radio receiver (MSP-102a, Initium Co., Sungnam, Korea) inside the rooftop. The receiver was a multi-serial Bluetooth server and wired to a host computer via TCP/IP ethernet.

A graphical user interface (GUI)-based irrigation software was developed and used for closed-loop irrigation control by integrating all input and output components of the system. The software allows real-time wireless communication with the PLC on the irrigation cart to receive GPS locations of the cart and send control signals for all sprinkler nozzle banks every second either automatically or manually after processing data for decision making. The software also allows a user to read an irrigation map at the beginning of the irrigation operation and save actual amount of water applied at each plot with GPS-referenced time and locations during the operation (Kim et al. 2007a).

Sensor Calibrations

The water content reflectometer was used to monitor soil water status. The reflectometer measures the volumetric water contents by using a time-domain reflectometry (TDR) method based on the dielectric constant of the soil (CS616, Campbell Scientific Inc., Logan, Utah). Two probe rods act as wave guides, and the dielectric constant of the soil surrounding the rods varies with the amount of water in the soil. The quality of soil moisture measurements is also affected by several other factors, such as soil electrical conductivity, clay content, and soil compaction, and thus the calibration has to be modified locally (Campbell Scientific Inc. 2004).

The TDR sensors were calibrated with a neutron probe (N-probe) (503D Hydroprobe Moisture Gauge, CPN International, Inc., Martinez, Calif.) that measures soil water status (factory calibration) at six different soil depths (23, 46, 61,76, 91, and 107 cm). Both TDR sensors and N-probe tubes were installed approximately 50 cm apart and monitored at five different locations on the soil EC field map (Fig. 1) during the 2006 growing season.

A malting-barley (cv. Legacy) crop was planted on April 14 with 67-kg/ha nitrogen (N), 50-kg/ha phosphorus (P_2O_5) and 11-kg/ha potassium (K_2O), and harvested on August 3. The field soil is a Savage silty clay loam (fine, smectitic, frigid Vertic Argiustolls) with 17% wilting point, 35% field water capacity, and 1.34-g/cm^3 bulk density. Measurements of the N-probe were conducted seven times (June 1, June 7, June 19, June 30, July 5, July 13, and July 18).

Volumetric water contents of the TDR sensor were compared to the N-probe (factory calibration) at the 23-cm (Table 1) 60-cm soil depths. The TDRs were read every 15 min., whereas the N-probe readings were measured about once a week. Data comparisons were made with the TDR readings measured at the same times as the N-probe readings.

A calibration equation was derived from a linear regression of the TDR compared to the N-probe. Fig. 2 illustrates volumetric water contents of both sensors at two soil depths at Station 1 under malting-barley and indicates a linear regression equation

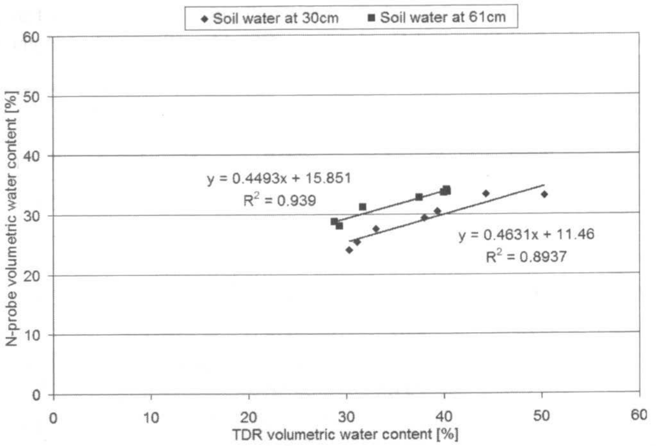


Fig. 2. TDR sensor readings compared to the neutron probe readings at two soil depths at Station 1 in 2006. Sensors at other four stations repeat the regression analysis.

and correlation of the TDR and N probe. Linear regression analysis was repeated for the other four stations to derive calibration equations.

Decision Making

Irrigation decisions were made based on the closed-loop feedback of soil water status with depth from the TDR sensors at all five sensor stations. The calibrated TDR response to water supply of rain (9.93 cm) and irrigation (6.63 cm) is illustrated in Fig. 3 during the entire growing season of 2006 (May 1–July 27) on the malting-barley crop. Each TDR sensor showed a different response range from dry to wet soil conditions. For instance, the TDR sensor in 30 cm at Station 1 has a response range of about 10% (varying from 27 to 37%), whereas the sensor in 61 cm has a response range of about 6% (varying from 29 to 35%), as shown in Fig. 3. High peaks on June 10 and June 27 were not included in the response range, because their readings were outliers caused by excessive amounts of water. Response ranges of sensors at the other four stations varied from a minimum of 3% to a maximum of 10%. The difference of the sensor's response range was caused by different levels of soil EC, clay, compaction, and imperfect installation. The response range of each sensor was assumed to remain from 2006 to 2007 experiment, because each sensor was used in the same soil depth at the same soil EC zone over two years. A slight response offset is expected, however, if the sensor is reinstalled into a different spot even in the same depth and at the same soil EC zone.

The response range of each sensor was monitored during the 2007 experiment and adjusted with an offset observed from 2006 data. Fig. 4 illustrates the TDR response to water supply of rain (9.80 cm) and irrigation (1.37 cm) for early growing season of 2007 (May 1–27). Irrigation on May 18 was applied on all five stations at the same rate of 1.37 cm water. The TDR response ranges in 30 and 61 cm show 4% (varying from 39 to 43%) and 7% (varying from 42 to 49%), respectively. As rain amount received for the month of May in 2007 was close to the total rain amount of the entire growing season of 2006, field soils were assumed to reach to the maximum wet condition, i.e., the upper limit of the response range. Thus, the highest reading of each TDR sensor at all five stations during May 2007 was selected for the upper limit of the response range and followed by the lower limit's adjustment in order to keep the response range obtained in 2006, as shown in Table 2.

The decision rule base for variable-rate irrigation was limited by a duty cycle of each sprinkler nozzle, i.e., on/off operations in a period of 60 s. For example, 100% water application turns on the nozzle for a full 60 s, whereas 40% water application turns it on only for 24 s, turning it off for the remaining 36 s. The manually selected travel speed of the linear move sprinkler system

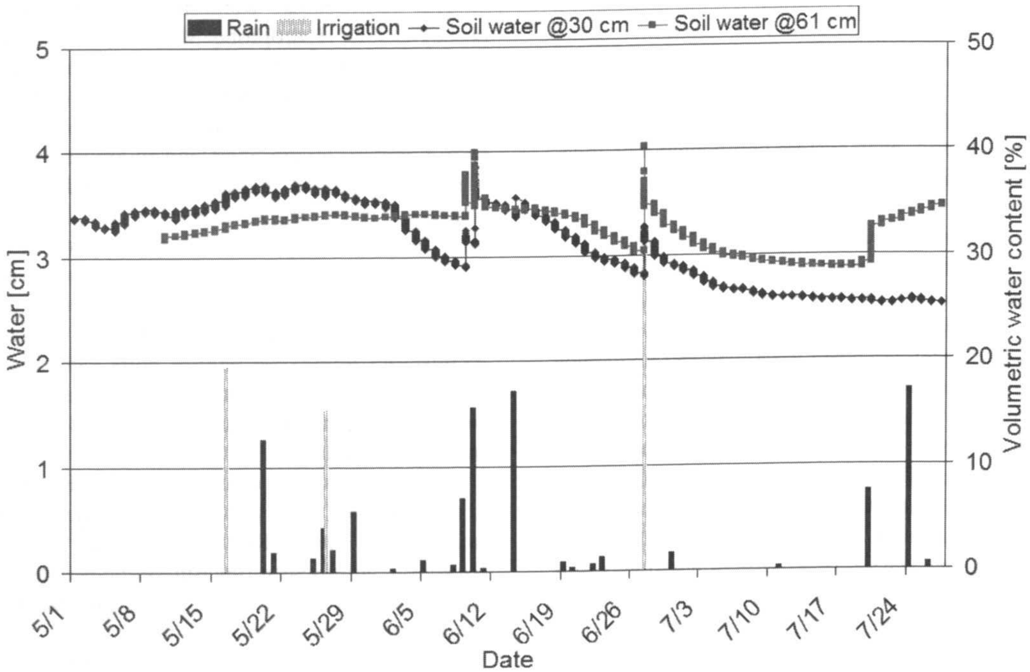


Fig. 3. Volumetric water contents of the calibrated TDR sensors in two soil depths at Station 1 during the entire growing season of 2006 (May 1–July 27) on malting-barley crop

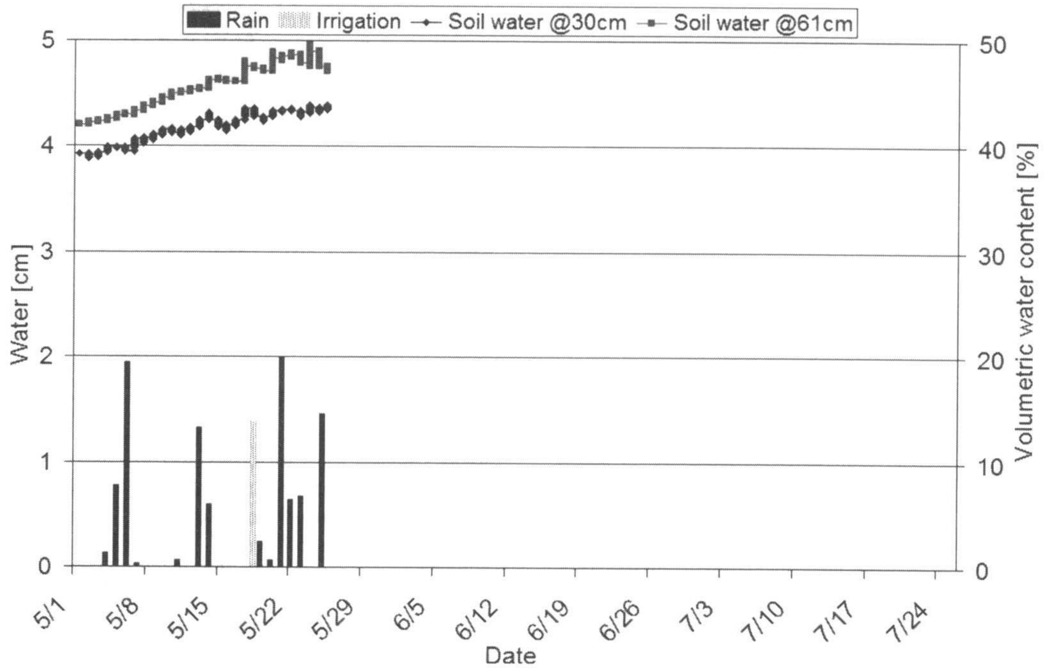


Fig. 4. Volumetric water contents of the calibrated TDR sensors in two soil depths at Station 1 during the early growing season of 2007 (May 1–27) on malting-barley crop

determined the maximum application depth. The output of the percentage of nozzle operation was determined by the deficit of the current TDR reading from the upper limit value of the range of each sensor to apply a percentage of maximum. Because the lower limit of the range indicates the driest soil condition, the desired soil moisture condition is selected as above the midrange of each sensor. When the deficit at any of five stations first reaches its midrange, the irrigation is triggered to apply for 100% water application and accompanied with irrigation on the rest of zones proportionally applied according to the deficit of their sensors. If the deficit falls below the midrange, the irrigation controller sends a signal for 100% water, whereas no water is applied if it reaches to the maximum, i.e., the wettest soil condition.

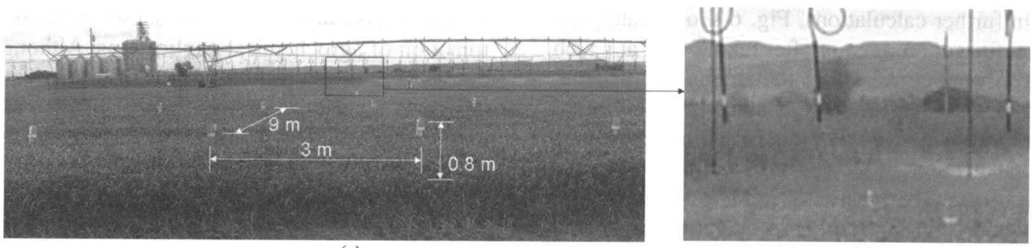
Table 2. Response Ranges of 30-cm Depth TDR Sensors of 2007 Determined Based on 2006 Data, Where the Range Remained but with Offset Applied

Station	2006 (May 1–July 27) Range (Min–Max) (%)	2007 (May 1–27) Range (Min–Max) (%)	2007 (estimated) Range (Min–Max) (%)
1	10 (27–37)	6 (37–43)	10 (33–43)
2	10 (32–42)	6 (41–47)	10 (37–47)
3	7 (30–37)	4 (37–41)	7 (34–41)
4	6 (30–36)	2 (41–43)	6 (37–43)
5	3 (30–33)	1 (33–34)	3 (31–34)
Average	7.2 (29.8–37)	3.8 (37.8–41.6)	7.2 (34.4–41.6)

Experiments and Results

The closed-loop irrigation control system was implemented and tested on an experimental field at the USDA-ARS-Northern Plains Agricultural Research Laboratory in Sidney, Mont. The 1.5-ha field was laid out in 15 strips in the direction of travel. Each strip was planted to malting barley. There are a total of 90 plots with the individual plots being 15 m wide and 9 m long. Each strip was divided into six plots [Fig. 1(c)]. All plots were irrigated with MESA sprinklers and blocked for replication.

Four catch cans were installed in the middle of each soil zone and aligned between two MESA sprinkler heads, spaced 3 m



(a) (b)

Fig. 5. Catch cans installed across a strip that contained all five soil zones and aligned between two MESA sprinkler heads. (a) Four cans were installed at each zone with 3 m apart and 0.8 m high. Each soil zone was located at a plot numbered 5, 6, 7, 9, and 10 from front to back. (b) Catch can 4 was misplaced and affected by a neighboring sprinkler.

Table 3. Variable-Rate Irrigation Amount Determined by the Feedback of TDR Soil Water Values at Each Soil Zone

Variable	Plot 5 (Zone 2)	Plot 6 (Zone 5)	Plot 7 (Zone 4)	Plot 9 (Zone 3)	Plot 10 (Zone 1)
TDR volumetric water content (%)	44.4	33.9	40.9	37.8	43.1
Percent of full (1 cm) irrigation (%)	52	7	70	91	0
Sprinkler duty cycle (s)	31	4	40	55	0
Actual irrigation (cm)	0.52	0.07	0.70	0.91	0.00

apart, and 0.8 m above the ground. Five sets of catch cans were installed across a strip that contained all five soil zones [Fig. 5(a)]. Each soil zone was labeled the same way as the station number and located at a plot numbered 5, 6, 7, 9, and 10 from front to back in Fig. 5(a). The total of 30 sprinkler banks were individually controlled by wireless signals transmitted from the base computer. Wireless radio signal stability and individual nozzle controllability for all 30 sprinkler banks were tested in a manual mode and visually identified before irrigation for catch can study. There was about 1 s. time lag in response of the PLC from the base computer via Bluetooth wireless communication and additional maximum 3 s delay in nozzle activation due to hydraulic power transition. The amount of variable-rate irrigation was applied by the percentage of full irrigation based on the ratio of the real-time update of TDR volumetric water content to its half range (=max–midpoint) of the sensor response at each soil zone (Table 3). For instance, 52% of full (1-cm) irrigation in Zone 2 was calculated by subtracting a current TDR reading (44.4%) from the max point (47%) of the response range, then divided by its half response range (5% =47-42%) in Table 2. The experiment was to evaluate how the irrigation sprinklers perform sensor-based real-time wireless control throughout the irrigation operation.

Catch cans data were collected on June 6, 2007. Catch cans at each soil zone were aligned from north to south and numbered from 1 to 4, respectively. Weather data were recorded at the weather station mounted on the downstream end of the lateral. The linear cart moved from plot 5 to plot 10 at less than 1 m/min speed for 1-cm irrigation at average wind speed range of 2.7–7.1 km/h and average wind direction of 187° (from south). South-neighboring sprinklers that were treated as conventional 100% water applications affected water distribution by wind drift and resulted in more water in south-side cans than north-side cans at all five zones, because the south-neighboring sprinklers (Fig. 1). Especially, Catch Can 4 was directly affected by the adjacent sprinkler, as shown in Fig. 5(b). Thus, data from Catch Can 4 were not included in further calculations. Fig. 6 shows catch can readings compared to irrigation amount after taking data at Catch Can 4. Catch can data were correlated to the amount of variable-rate irrigation with 0.96 r^2 value, though catch cans collected average 0.23 cm of more water out of 1-cm irrigation, caused by the wind drift effect.

Signal multipath of the GPS was observed five times when a GPS signal error occurred during the entire operation of 82 min from 9:46 to 11:08 a.m. Three errors were caused by signal bouncing at a plot boundary: once between Plots 5 and 6, and twice between Plots 7 and 8. Two errors were signal loss or bouncing out of experimental plots. Each occurrence was a single signal bouncing and took only a second to return to a correct GPS position. As signal strength of the GPS is affected by atmosphere and cloud, this is not unusual. This 1-s signal change is inactivated in 3-s hydraulic delay and does not affect the irrigation rate.

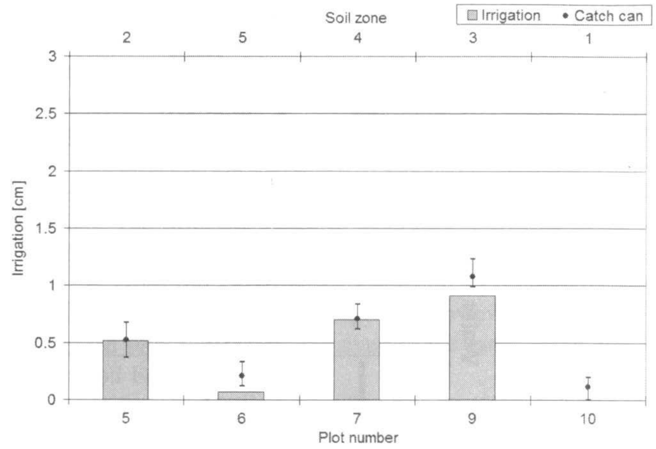


Fig. 6. Catch can readings compared to irrigation amount at wind speed of 10–15 km/h on June 6, 2007 when the linear irrigation cart moved from Plots 5–10

Conclusions

An automated closed-loop irrigation control system was developed and tested with a self-propelled lateral-move sprinkler irrigation system that was set up for site-specific variable-rate water applications. Real-time wireless communications were seamlessly interfaced between in-field sensing stations, a variable-rate irrigation control station, and the base station by using Bluetooth radio technology. An experimental field was mapped and configured into five separate control zones based on soil electrical conductivity for the distribution of the wireless sensor network. Soil water sensors were individually calibrated within each zone with a neutron probe for 30- and 61-cm soil depths. Variable-rate irrigation was determined by feedback of soil water status from sensor stations. User-friendly software was developed to interface the base station with a PLC irrigation controller and wireless in-field sensor network for GUI-based real-time irrigation control and monitoring. The software tracks GPS locations of the irrigation cart and sends individual control signals to the 30 sets of sprinkler nozzle banks every second either automatically or manually on request. The irrigation sprinklers successfully followed real-time wireless control signals throughout the irrigation operation without interruptions in wireless radio communication. Catch can data were highly correlated to the water amount applied with r^2 =0.96. The benefit of the closed-loop control for a site-specific irrigation system with wireless sensor network will extend to automation of agrochemical applications. Although While this technology was developed on a linear move irrigation system, it was designed to also work with center pivots. The next step is to extend this technology to a grower's field for their evaluation and testing.

References

Ahmad, I. S., Reid, J. F., Noguchi, N., and Hansen, A. C. (1999). "Nitrogen sensing for precision agriculture using chlorophyll maps." *ASABE paper No. 99-3035*, ASABE, St. Joseph, Mich.

Campbell Scientific Inc. (2004). *CS616 and CS625 water content reflectometers—Manual*, Logan, Utah.

Drummond, P. E., Christy, C. D., and Lund, E. D. (2000). "Using an automated penetrometer and soil EC probe to characterize the rooting zone." *Proc., 5th Int. Conf. on Precision Agriculture*, Springer, The Netherlands.

Evans, R. G., and Iversen, W. M. (2005). "Combined LEPA and MESA irrigation on a site specific linear move system." *26th Annual Irrigation Association Int. Irrigation Show*, IA05-1298, Curran Associates Inc., Red Hook, N.Y.

Farahani, H. J., and Buchleiter, G. W. (2004). "Temporal stability of soil electrical conductivity in irrigated sandy field in Colorado." *Trans. ASABE*, 47(1), 79–90.

Irmak, A., Jones, J. W., Batchelor, W. D., and Paz, J. O. (2002). "Linking multiple layers of information for attribution of causes of spatial yield variability in soybean." *Trans. ASABE*, 45(3), 839–849.

Jabro, J. D., Evans, R. G., Kim, Y., Stevens, W. B., and Iversen, W. M. (2006). "Characterization of spatial variability of soil electrical conductivity and cone index using coulter and penetrometer-type sensors." *Soil Sci.*, 171(8), 627–637.

Kim, Y., Evans, R. G., and Iversen, W. M. (2007a). "Decision support and monitoring for wireless sensor-based site-specific sprinkler irrigation." *ASABE Paper No. 073078*, ASABE, St. Joseph, Mich.

Kim, Y., Evans, R. G., and Iversen, W. M. (2007b). "Remote sensing and control of an irrigation system using a wireless sensor network." *IEEE Trans. Instrum. Meas.*, 57(7), 1379–1387.

Kim, Y., Evans, R. G., Iversen, W. M., and Pierce, F. J. (2006a). "Evaluation of wireless control for variable rate irrigation." *ASABE Paper No. 062164*, ASABE, St. Joseph, Mich.

Kim, Y., Evans, R. G., Iversen, W. M., Pierce, F. J., and Chavez, J. L. (2006b). "Software design for wireless in-field sensor-based irrigation management." *ASABE Paper No. 063074*, ASABE, St. Joseph, Mich.

Kim, Y., Evans, R. G., and Jabro, J. D. (2005). "Optimal site-specific configuration for wireless in-field sensor-based irrigation." *26th Annual Irrigation Association Int. Irrigation Show*, IA05-1307, Curran Associates Inc., Red Hook, N.Y.

King, B. A., Wall, R. W., and Wall, L. R. (2000). "Supervisory control and data acquisition system for closed-loop center pivot irrigation." *ASABE Paper No. 002020*, ASABE, St. Joseph, Mich.

Miranda, F. R., Yoder, R., and Wilkerson, J. B. (2003). "A site-specific irrigation control system." *ASABE Paper No. 031129*, ASABE, St. Joseph, Mich.

Perry, C. D., Dukes, M. D., and Harrison, K. A. (2004). "Effects of variable-rate sprinkler cycling on irrigation uniformity." *ASABE Paper No. 041117*, ASABE, St. Joseph, Mich.

Shock, C. C., David, R. J., Shock, C. A., and Kimberling, C. A. (1999). "Innovative, automatic, low-cost reading of Watermark soil moisture sensors." *Proc., 1999 Irrigation Association Technical Conf.*, The Irrigation Association, Falls Church, Va., 147–152.

Wall, R. W., and King, B. A. (2004). "Incorporating plug and play technology into measurement and control systems for irrigation management." *ASABE Paper No. 042189*, ASABE, St. Joseph, Mich.